causal role of the error, which is itself emergent, is not nearly *so* robust. Certainly it has consequences, but it cannot be described as "self-maintaining" in the sense that stable attractors in self-organizing systems are self-maintaining. The basin of attraction of the error is much smaller; the error is more a one-time thing. The memory, on the other hand, serves an organizing role in coordinating the subprocesses ("looking, planning, reaching") to produce the error. Thus act/object representation is a vital component of DST, and not a useless fossil of an extinct cognitive theory.

Clothing a model of embodiment

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Abstract: By delineating the parametric variations that affect infant performance in the standard A-not-B search task, the Thelen et al. model provides an important contribution to the field of infant development. We discuss several broad issues pertinent to interpreting the model. We note that the phenomenon modeled by Thelen et al. is not necessarily the one originally described by Piaget. We describe data on infant self-correction that are not addressed by the Thelen et al. model. Finally, we suggest that psychological constructs such as representation and knowledge structures are valuable to our understanding of the A-not-B phenomenon in particular and psychological development in general.

If Kurt Lewin were alive, he would probably be very pleased with Thelen et al.'s approach to modeling the dynamics of behavioral development. Unfortunately, his efforts to apply the principles and methods of topology to the development of a psychological field theory remained in the realm of metaphor due primarily to the unavailability of sophisticated computational power. Nonetheless, Lewin argued persuasively for studying the dynamics of the endogenous and exogenous forces that influence a child's cognitions and social behavior in the actual and total situation of which they are a part (Lewin 1936; 1954). In some sense, the Thelen et al. model realizes Lewin's prescient vision.

In contrast, Jean Piaget would probably not be very pleased with the Thelen et al. approach. For one thing, the phenomenon that he describes in *The construction of reality in the child* (1954) as the typical reaction of the fourth stage is notably different from the phenomenon that is now generally accepted as the A-not-B error. Here is Piaget's description of the reaction:

> Suppose an object is hidden at point A: the child searches for it and finds it. Next, the object is placed in B and is covered before the child's eyes; although the child has continued to watch the object and has seen it disappear in B, he nevertheless immediately tries to find it in A! (1954, p. 54)

Clearly Piaget did not posit multiple hidings at location A as a prerequisite for incorrect search at location B. In one observation of Jacqueline at 0; 10, the object is hidden at location A twice but in observations of Lucienne and Laurent, there is usually only one hiding at location A. For example,

> Obs. 42. At 0; 10 (9) Lucienne is seated on a sofa and plays with a plush duck. I put it on her lap and place a small red cushion on top of the duck (this is position A); Lucienne immediately raises the cushion and takes hold of the duck. I then place the duck next to her on the sofa in B, and cover it with another cushion, a yellow one. Lucienne has watched all my moves, but as soon as the duck is hidden, she returns to the little cushion A on her lap, raises it and searches. An expression of disappointment; she turns it over in every direction and gives up. (1954, p. 57)

This point is vitally important here because it is not obvious that the Thelen et al. model would predict a strong tendency toward perseveration after a single trial at location A. The vast literature based on the Uzgiris and Hunt (1975) formalization of the A-not-B error using a task with multiple hidings at location A raises very interesting phenomena, many of them well captured by the Thelen et al. model. Whether or not this literature is about Piaget's "typical reaction of the fourth stage" is an open question.

Second, given Piaget's interest in the acquisition of knowledge, he would surely balk at Thelen et al.'s contention that there is no transcendent knowledge. A person with no implicit belief in the permanence of objects would have no reason for searching for missing keys. Adults clearly have the insight that objects continue to exist when out of sight. Young children have this insight and infants might have it too. Indeed, there is some utility in positing that infants "know" where something is hidden despite reaching for it incorrectly. For example, consider findings reported by Reznick et al. (1998). In two experiments, 9-month-old infants saw an object hidden in one of three locations. Infants who reached incorrectly were allowed to search again in one of the two remaining locations. Despite a long delay between hiding and search (10- to 20-sec), infants responded correctly more often than would be expected by chance on their second reach. Some sort of adjustment of the Thelen et al. model might be evoked to explain this result, but it is hard to escape the straightforward claim that the infant has some knowledge of the object's location but is distracted from acting upon this knowledge in the initial search.

The Thelen et al. model is a vital contribution to the field because it delineates the parametric variations that affect infant performance in a standard search task (e.g., variations in stimulus identity, response modality, number of potential hiding locations, and length of delay). Nonetheless, we believe that the changes in performance observed across these variations are better viewed as different windows on the infant's underlying knowledge structures. This perspective has led us to realize the importance of a research strategy that examines infant performance on a search task under assorted task variations.

It is certainly healthy for the field of developmental psychology to question what is meant by the claim that the infant knows something (about objects or physics or mathematics or other minds). However, to discard the possibility that the infant can have any knowledge whatsoever is excessive. Our field has been down the logical positivist road, and we are sadly familiar with the intellectual and scientific stagnation associated with strong behaviorism. Mathematically rigorous modeling is generative and refreshing, but it is vacuous without terms representing plausible psychological content.

Cooperative field theory is critical for embodiment

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Abstract: The field theoretic approach of the target article is simplified by setting the parameters of the dynamical field equation so that the system is near the critical point between cooperative and non-cooperative dynamics. However, embodiment of cognitive development would require a closer connection between the dynamical field interactions and the physiology of the cerebral cortex.

1. Interactions are critical. Thelen et al.'s target article presents an interesting and potentially fruitful approach to deepen our knowledge about the neural basis of cognitive behavior. By focussing on the motor aspects of cognition, the authors are able to bring insights to bear on the problem of cognitive development that are drawn from motor development. This approach also succeeds in elevating motor control from the mire of control theory, thus blending motor activity with the so-called "higher" functions.

However, the field dynamics contain extraneous parameters that are unnecessary for the prediction of dynamics described in the target article. Under the proper parameter settings, the cooperative (interactive) term in the field equations will lead to phase transitions that generate the desired dynamics. By emphasizing the dynamics arising from the interaction term (sect. 4.1.3), the task input (sect. 4.2.1), $S—{task}(x, t)$, and the memory input (sect. 4.2.1), $S—{mem} (x, t)$, become redundant.

The interaction term introduces instabilities into the system so that the choice of A versus B arises from small perturbations of the dynamic field (sect. 4.1.1), $u(x, t)$. These instabilities are analogous to those in the visual system that have been suggested as an underlying mechanism for certain visual hallucinations (Ermentrout & Cowan 1979). In the present case, the instabilities lead to cooperativity that represents movement direction probabilities in the space of motor activity.

By encapsulating the cognitive choice of the hidden toy's location in terms of motor representations, the authors are able to tie their formalism to population codes (Georgopoulos 1996). The connection would be more complete if the memory were embedded in neural structures of the cerebral cortex. If the theory were truly "embodied," then $S— {mem} (x, t) $ inputs might be contained in the interaction term and represent synaptic interactions.

2. Critical fields persevere. Analysis and simulations can be used to study pattern formation on the one-dimensional domain that represents the movement space. The following analysis shows the existence of instabilities that yield a phase transition in the configuration space of the field $u(x, t)$. Results of simulations are presented that yield the behavior near the critical point of the phase transition between disordered and fixed behavior. Because the movement space is represented as the direction of reach from the sitting child, the domain encompasses a circle. The fixed behavior would appear as oscillations in the field value around the circle. High field values over a particular value of x would represent a high probability of a reach in that direction.

To find the natural wavelength generated by the interaction term our starting point is the field equation (3), $τ {u̇}(x, t)$ = $ − u(x, t) + S(x, t) + g(u(x))$. The interaction term is a convolution of a threshold function of the field, $f(u(x))$ with the interaction kernel. To simplify matters for the analysis (we use the exact expression in the simulation) , we can expand the threshold function so that, $f(u(x)) = u(x) + t\cdots$. To seek instabilities in the absence of perturbations ($S(x, t=O$) , we assume an oscillatory solution, $u(x, t)=e^{λ t}e^{ikx}$ and see whether it yields solutions to the field equations. Instabilities decay if the growth factor $λ$ is negative for all wave numbers k otherwise oscillations exist.

The result is that oscillations appear on the order of the system size. That is, a single reach direction will appear as a region of high field activity, and the reach will be frozen in that direction. Thus the frozen phase spontaneously generates the task input, $S—{task} (x, t)$. However, with sufficient noise in the system, the instability is overwhelmed and there would be no preferred direction so that no reaching is manifest. If the noise, or the interaction kernal, is properly tuned *so* that the *system* is near the transition, then spontaneous reaching occurs in random directions. A simulation confirms these analytic results, as shown in Figure 1. In this simulation, the field $u(x)$ is discretized into a set of interacting units, and the noise is set so that the field solution is near the critical point. Two perturbations are introduced: a cue to target A, $S— {task}(x)$, and a memory of target B that is encoded as a slight increase in the interaction kernel in the vicinity of target B. In this simulation, the memory does not fade.

Spontaneous switching between the two targets is seen in part A of the figure. The simulation also shows another feature of field behavior near the critical point: high susceptibility. The region of high field activity is the result of very small perturbations, so small that no result would he seen in higher noise conditions. Part B of the figure shows the result of an average over many trials for three different intensities of the cue. It is interesting that there can be stronger memory behavior with a small cue (dashed trace) than with no cue at all (dotted trace).

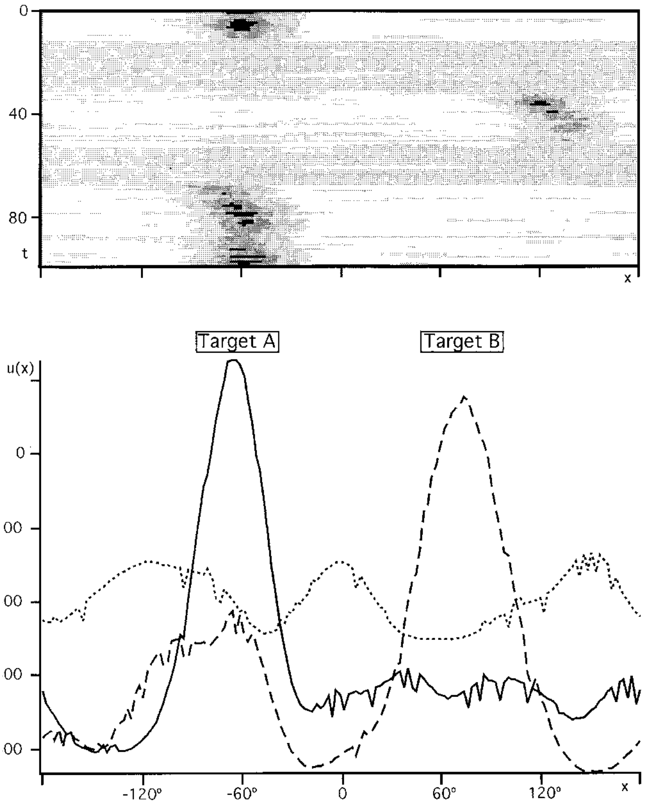

Figure 1 (Roberts). Simulation of field dynamics near the critical point. The cue input is located at target A (−60^{o}) and the interaction is slightly increased at target B (70^{o}) to represent memory effects. (A) Dynamical field amplitude of $u(x,t)$. Grey scale represents amplitude from lowest (white) to highest (black). Random switching takes place between target A ($t \in$[1,13] and $t \in$ [67,100], target B ($t \in$[32,54]), and non-cooperative dynamics ($t \in$[14,31]) and ($t \in$[55,66]). (B) Average of the dynamical field amplitude over $t \in$[1,4000] for simulations with no cue input (dotted trace), moderate cue input (dashed trace), and large cue input (solid trace).

3. Critical connections to the brain? The conclusion we may draw from this exercise is that undecided movements crystallize into a decision as the system balances on the edge of a critical point. In the target article, the weak link to embodiment is in the physiological connection to motor population coding (Georgopoulos 1996). The memory term could be embedded in the interaction term with synaptic interaction yielding the form of the interaction kernel and perhaps synaptic plasticity regulating the strengths of the synapses. This is not unrealistic, given the known cortical interactions of local excitation and lateral inhibition. However, embodiment of the theory would require a kind of "kinetopy" that has not been found in the motor cortex. In their attempt at embodying cognition, the authors must be careful not to "disembody" motor control.